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Study of the temporal characteristics of friction and contact behavior encountered during braille reading

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ABSTRACT

Beyond the sense of sight, the sense of touch is one of the primary ways that individuals experience their surrounding environment. Fundamentally understanding the relationship of skin-surface tribology and its elicited tactile attributes could provide a breakthrough in improving the ability to efficiently transmit tactile information to those who rely on the sense of touch to interact with their surroundings, such as the blind and visually impaired (BVI) community. The tactile language of braille has been adopted by the BVI community, employing configurations of raised dome-shape dots to convey what is ordinarily presented in text and image form. The coefficient of friction caused by skin sliding across a these dot features is hypothesized to affect the reader's tactile sensitivity, and skin-on-braille coefficient of friction has been investigated in previous work, where macro-scale deformation of the human fingerpad sliding over the dot contour was identified as the dominant friction mechanisms. This investigation succeeds that study by examining a simplified large-scale, two-dimensional representation of skin-on-braille sliding to characterize the underlying contact mechanisms in the loading behaviors that dictate the resulting coefficient of friction. This was accomplished by using a multi-axis tribometer to sliding a 25.4 mm radius cylindrical polyurethane (representing a human fingerpad) rod over a lubricated 3.17 mm aluminum half rod (representing a braille dot) under displacement-displacement-controlled conditions. The results from the tribometer study indicate that the presence of the dot feature drastically affects the vertical and lateral loading behavior by vertically displacing the body's elastic bulk, generating rubber-like Poisson effect contributions. Most importantly, the Poisson effect rapidly increases the lateral load when the body contacts the dot's leading edge, and rapidly decreases when the body rests largely in contact with the dot's trailing edge. This rapid decrease is caused by a “propulsion” effect, where vertical compression expands the material laterally, and when situated on the trailing edge of the dot, propels it into the direction of sliding, virtually negating adhesive surface friction. Computational modeling of this system discovered that while normal contact pressures dominated the fluctuations seen in the vertical loading, effects due to both normal contact pressures and frictional shears nearly equally drove the lateral loading behavior.

1. Introduction

Touch is one of the fundamental sensory mechanisms that allow individuals to physically interact with and learn about their surrounding environment. Tactile exploration is generally not the primary method that individuals use to acquire information, for this designation would be given to the sense of sight. Unfortunately, not all individuals possess the ability to employ vision as their principal means of learning; and as a result, the blind and visually impaired (BVI) community relies on touch and tactile perception. Varying types of tactile language were developed in order to provide non-sighted with the tools to learn with and function in the same way that sighted individuals can, and the braille writing system was adopted as the standardized tactile language for the BVI community.

Perceiving and decoding the braille language requires an individual to tactually scan the text or images with the fingerpad, and this form of tactile perception is governed by the tribological skin-surface sliding interaction experienced during the exploration of the dot configurations. It is believed that during this sliding interaction, the resulting changes in coefficient of friction (COF) aid the reader in translating the code, in the same way that coefficient of friction has been believed to influence perceived tactile attributes in other surfaces such as paper media [1,2], or textile fabrics [3–8], or ridged textured metals and polymers [9,10]. In the case of skin sliding over featureless paper media, Skedung

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et al. found that coefficient of friction was positively correlated to both perceived coarseness as well as the media's surface roughness [1,2]. Conversely, friction correlations to tactile perception have not been as prominent for skin interactions with textiles or ridged surfaces. Highly specific attributes such as abrasiveness or softness were not found to be related to skin friction [6], but perceived comfort and friction have been positively correlated for both wearable textiles as well as rigid textures, primarily influenced by the degree of moisture at the skin-surface interface [3,4,7]. Complementary to this finding, variations in surface topographies with macroscopic features have been found to produce skin deformations and surface vibrations that in turn affect friction and perception [8,9]. While not explicitly dictating tactile perception, skin friction and its interaction with topographical surfaces still affect the tactile experience to some degree, and understanding these sliding interactions would prove valuable for a multitude of applications.

Understanding the fundamental friction and contact mechanics of the skin on braille dot tribology would allow for a deeper understanding in friction's impact on the quality of learning and perception for the BVI community. The tribological interaction of a human fingerpad sliding over a braille dot is analogous to Wolfram and Adams' model of a small rigid sphere being dragged across an elastic half-plane [11,12] (based on Greenwood and Tabor's [13,14]), and this model was key in discovering the major impact that the friction mechanism of deformation has on coefficient of friction behavior during skin-dot sliding [15]. During this investigation, the trends exhibited in the coefficient of friction behavior were investigated, but the specific contact mechanisms driving the loading behavior, which in turn dictated the COF, were not analyzed.

The purpose of this investigation was to determine the underlying contact mechanisms that drive loading behavior during braille reading. It was hypothesized that the vertical loading behavior, and in turn lateral loading behavior, was primarily driven by bulk material deformation during sliding, varying the degree of contact normal to the surface topography, and this was tested in two phases. The first aspect of the study was to observe the vertical and lateral loading behavior of a large-scale, two-dimensional representation of a simulated braille reading. The second aspect of the study sought to further understand the data and claims drawn from the initial phase by performing computational modeling and decomposing the loading components and coefficient of friction behavior.

2. Materials and methods

Previous work has determined that the friction mechanism of deformation plays a major role of sliding interactions during braille reading, where a soft fingertip slides against a rigid braille dot feature [15]. The motivation for this study was to gain a better understanding of the exact contact mechanics that occur during this tribological interaction. This paper investigates the force interactions and presents two phases that were performed concurrently in order to complement and validate the other's data and analyses.

2.1. *Empirical study of a soft cylindrical body sliding over a rigid half-cylindrical feature*

The first phase of this investigation explored the contact mechanics of braille reading by recreating the tribology of braille reading in a large-scale, yet simple manner. While braille reading involves forces and deformations in three directions, this design simplified the problem by reducing the finger's and dot's spherical geometries to cylindrical bodies. Here, sufficiently long cylinders assume plane strain conditions, where strains and forces were restricted to only two directions in order to be analyzed more easily. The testing during this phase employed a multi-axis tribometer (Rtec Instruments) for all sliding interactions and force measurements.

The projected contact area of the human fingerpad is ellipsoidal in shape, but as observed in previous work [15], it can be assumed to be a homogeneous, elastic spherical (for this sake of this study, cylindrical) body. Typically, one measures approximately 20 mm across (10 mm radius), and the standard hemispherical braille dot is 0.48 mm high. This comparison yields roughly a 20:1 scale between fingerpad and dot feature radii. Due to the availability of commercial materials (i.e. the aluminum half cylinder), the scale of the finger-to-dot ratio in this study was reduced to 8:1. A 50.8 mm (2 in.) diameter polyurethane rod was selected to simulate the finger's elastic behavior. The polyurethane rod had a durometer hardness rating of 40 A, and according to Eq. (1),

$$E = \left[S_A \cdot 0.0235 - 0.6403 \right] \tag{1}$$

it had an equivalent modulus of elasticity of 1.35 MPa, where E is the modulus of elasticity in MPa and S_A is the ASTM D2240 type A hardness rating. The rod was cut to 30 mm in length so that the loads produced from the required displacements would not exceed the limitations of the tribometer's load cell. Polyurethane was selected to represent the human fingerpad as it, along with silicone, has been shown to successfully exhibit frictional and mechanical properties as mechanical skin equivalents [5]. While the skin fingerpad is a textured surface covered in ridged surface textures, this study ignored these textures in order to solely focus on observing bulk material deformations due to the introduction of a macroscopic topography, absent of surface interactions.

The rod's circular cross-section was squared off on three of the four sides so that it could be mounted into a stainless steel U-channel. This was performed in order to ensure that both the vertical and lateral displacements were uniformly applied, as well as to eliminate rotation due to sliding. This mounting treated the rod as a half cylinder where applied displacements and boundary conditions could be maintained at the vertical center of the cylinder. A stainless steel shaft was welded to the top surface of the channel to mount to the tribometer's load cell.

The dot surface counterface consisted of a 6.35 mm (1/4 in.) diameter aluminum half cylinder affixed to 6.35 mm (1/4 in.) thick 152.4 mm × 152.4 mm (6 in. × 6 in.) aluminum plate. The top surface of the counterface was manually polished with P2500 grit abrasive paper and subsequently cleaned. This counterface was then mounted to the tribometer's dual-axis, stage, and the final experimental setup can be seen in Fig. 1.

A 6D, 500N limit load cell was used to record both the vertical and lateral forces at a sampling rate of 1000 Hz during all sliding tests. Additionally, the tribological tests were performed under displacement-controlled conditions in an environment where temperature and humidity measured at 23.8 deg. C and 50% humidity, respectively. Vertical displacements were controlled by the Z-axis motor and load cell suspension, and lateral displacements were controlled by the dual-axis stage (X-axis only). Additionally, a GoPro HD camera was mounted to the stage to record video of the rod sliding across the surface. This footage was then synchronized with the force data to visualize the sliding interaction with respect to the data's loading behavior.

Because this study sought to isolate and understand the sliding mechanics caused by a large scale feature (not due to small-scale surface interactions), the surfaces of both the polyurethane rod and counterface were coated with a thin film of food-grade mineral oil lubricant. Additionally, the lubrication reduced the